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CONDITION OF THE HUMAN CARDIOVASCULAR SYSTEM IN TRUE AND SIMULATED WEIGHTLESSNESS

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ABSTRACT: The experience of manned space flights proves that weightlessness also has an effect on the cardiovascular system. Experiments were conducted, measuring diastolic, mean, marginal, and terminal systolic pressure, velocity of pulse-wave spread frequency of heartbeat, length of phase of the cardiac cycle, pulse, and minute volume of blood.

The accumulated experience of space flights does not leave any doubt that staying in weightlessness changes the condition of the cardiovascular system. It is therefore very important to know to what extent this fact limits the permissible duration of space flights. /1*

It is equally important to know whether it is possible to forecast the period of flight safety from information on the hemodynamic condition during flight. Finally, it is essential to make clear to what degree of approximation the results obtained at simulated weightlessness in terrestrial experiments would permit an answer to the questions posed above.

From the point of view of mechanics, the heart and vessels are not built from the best material. Their pliability is such that hydrostatic forces can produce disturbances in blood circulation by interfering with the distribution of blood. Its stiffness must be corrected with a system of antigravity regulators, so that a structure made of a material pliable to the effect of blood weight will work. Facts discovered by physiology during the study of acute orthostatic reactions [7, 8] allow to suppose that the biophysical operating principle of these regulators consists of contraction of the muscular elements of vessels at the moment when they are subjected to intensified stretching and vice versa. Practically speaking, antigravity skeletal muscles also act according to the same principle. The difference lies in the fact that the stiffness of vessels is regulated not only by neural mechanisms but also by their own myogenic mechanisms.

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* Numbers in the margin indicate pagination in the foreign text.

However, we undoubtedly change our low evaluation of the mechanical properties /2 of the heart and vessel material, if we remember another truly marvelous property of living tissues - the ability to so change their proper mass that it will strictly correspond to the magnitudes of functional loads.

Vessels of high and low pressure systems having the same radius are markedly different as to the thickness of their walls. Evidently, the tension in their wall is a morphogenetic factor that determines the vascular structure. As is well known, this is proportionate to the product of the vessel's radius and its pressure.

But the radius of vessels, as a value on which their resistance to the blood flow also depends, must under all conditions meet the task of tissue nutrition. Value of arterial pressure must also meet the same task. Therefore, at relative rest, both these parameters are more or less fixed by the value of the blood flow required for the tissues. The only method to balance the tension of vessel walls in accordance with the ordinary intensities of mechanical loading, pressure, is to develop a wall thickness sufficient for this.

At the same time, we note that the thicker the vessel wall, other conditions remaining the same, the more effective the influence of sympathetic impulses will be upon it /3, 9/.

Just like other authors, we are inclined to think that the blood circulation of man is adapted to man's current activity, and consequently, also to the vertical position. Does it not follow either from this, or from the earlier statements, that the morphological organization of human vessel walls /3 provides some reserves that are specially intended to compensate for the rather expansive force which the blood weight creates?

Don't these reserves prove to be excessive for the conditions of weightlessness?

Experiments on animals permit us to simulate the effect of disappearance of the hydrostatic component of pressure by way of constriction of an organ's main artery. The drop in the absolute value of pressure distally to the place of constriction is physically equivalent to relieving the wall of resistive vessels from the action of the hydrostatic component of pressure.

In experiments on rats, with a small helical spring, we constricted a section of the aorta somewhat higher than its bifurcation (Figure 1). The degree of constriction was so selected that in the femoral arteries the average pressure dropped to approximately 50% to 60% of the initial pressure. Two months after the operation, the pressure in the carotid artery was on the average equal for the group of animals - 114 mm Hg, whereas in the femoral artery it was 68 mm Hg, i.e., lower by 40%. In spite of this, the average magnitude of blood flow through the hind extremity equaled precisely the average magnitude of blood flow in the control group: in both cases, it was 0.8 ml/min (Figure 1).

If the normal perfusion pressure is restored by uniting the vessels of the extremity with the carotid artery, then the blood flow increases to 1.65 ml/min, i.e., more than doubles the flow required for the tissues. From this fact it can be concluded that chronic constriction of the arterial pressure in vessels of the lower half of the body leads to an increase in their expansibility.

Evidently, a consequence of this is the diminution of the reactivity of re- /4
sistive vessels of an extremity to the tonic pulsation of sympathetic constrictors. In the control group of experiments, section of the femoral and sciatic nerves increases the blood flow through the vessels of the extremity by an average of 80%. In rats, however, with a chronic constriction of the arterial pressure beyond the aortic bifurcation, it increases by 6%.

The vessels which are weakened by the effect of a stretching force and to the compensatory influence of constrictor impulses are functionally analogous to a shunt through which there is an escape of blood into the venous bed, unjustified by a metabolic demand.

With any significant fault, the mean arterial pressure can fall. The organism will have to put into action a certain portion of compensatory reflex reactions in order to eliminate this, first of all, the acceleration of heart beat. It is known that this also restricts the dynamic range of these reactions in situations of truly increasing demands and leads to a picture of hyperreactive sympathetic stimulation.

We ventured to begin our report with the discussion of the very first results of recently begun simulating experiments on animals, taking into consideration the difficulties which arise in understanding the mechanisms of hemodynamic changes when simulating weightless conditions in man.

Research on man is complicated by a mass of attendant factors that are difficult to understand. Hence, we have a diversity of results that acquires special expressiveness with the employment of blood methodology.

And even these methods themselves, with all their preciseness (we have in /5 mind, e.g., the staining or direct method of Fick for the determination of the minute volume of blood circulation) are far from being the best for the display of rapidly occurring transitional processes.

In our investigations, we used a complex methodology consisting of the simultaneous recording of the tacho-oscillogram of the humeral artery, sphygmogram of the humeral and femoral arteries, kineto- and electro-cardiograms. Recordings determined the diastolic, mean, marginal, and terminal systolic pressure, the velocity of pulse-wave spread frequency of heartbeat, length of phase of the cardiac cycle [2], and we calculated the pulse and minute volume of blood according to the Bremzer-Ranke formula as modified by Prof. Savitskiy [4].

The choice of these methods was determined by their noninjuriousness and ease of repeated or lengthy continuous measurements. However, when selecting the methods, the main principle consisted of a compromise between the necessity of comparing and analyzing a possibly large number of simultaneously considered indices pertaining to various links of the cardiovascular system, and the possibility of using these or other methods during flight.

We realize the inevitable inaccuracy of determining the minute volume of blood circulation by means of an indirect calculating method. However, the great experience in its use allows us to state that it correctly represents the trend and the relative range of minute volume change under such influences as physical stress, provocation of negative pressure on the lower half of the body, and the orthostatic test, and it yields results which are fully reproducible during repeated examinations of a given man [5].

From the available material it seemed to us appropriate to scrutinize some /6 results of a 30-day experiment in which a clinostatic position (4° head down from the horizontal) was observed which simulates the effects of the redistribution of blood in weightlessness. One of the groups included three examinees. One of them, S., has a decreased tolerance to negative pressure at the lower half of the body. The other, N., occupies an intermediate position. The most resistant is K., who in addition had a trial participation in an analogous experiment that lasted 70 days.

The hemodynamic indices were measured twice a week before the start of the experiment, and seven times during the experiment, including three times at full rest, and four times for 5 to 10 minutes before the tests with negative pressures of 35 to 45 mm Hg with exposure at each regime of ten minutes.

From the obtained data, it follows that during the experiment the deviations of basic hemodynamic values were insignificant. More marked were the pulse acceleration and the increase in the mean arterial pressure in S. Pressure increase was approximately the same in N., in whom one could also notice a tendency toward reduction of the minute volume of blood circulation (Figure 2).

As was to be expected, the change in blood circulation in response to the functional load as the experiment progressed, proved to be very marked (Figure 3). The symptom of reduction of stability already appears by the end of the first week. However, a clearly growing tolerance deterioration to functional tests cannot be observed during a 30-day experiment.

We emphasize that in each examinee the individual characteristics of hemodynamic reactions to the functional tests were also preserved. /7

It is well known that for space flight, it is important to make clear to what extent the production of a negative pressure around the lower half of the body permits the prognostication of the result of an orthostatic reaction.

The obtained data are indicative of an unquestionable tie between the reactivity of the examinee to both kinds of influence. This is obvious from the example of the second group of examinees who during the experiment carried out special complicated physical training (Figure 4).

And so, a picture of stress of the compensatory reactions of blood circulation is evident, clearly manifested in marked acceleration of the pulse, increase in the mean arterial pressure, and velocity of spreading of the pulse wave. What kind of interpretation can be given to this picture of hyperreactivity? After hypodynamia, why do the systems of blood circulation antigravity control have to work at a higher level of their dynamic range? Naturally, first of all, one thinks of an increase in perturbation, i.e., of changes induced by gravitational factors in the blood distribution.

It is true that the question of whether the pliability of capacitive vessels increases after hypodynamy, or vice versa, is reduced, is still debatable [1, 8]. In any case, the diameter of these vessels increases under the effect of the hydrostatic pressure, and since the thickness of their wall is small, a considerable stress develops in the wall.

In such a state, the regime of the contraction of muscles of these thin- /8
walled vessels comes close to the isometric, in other words, the possibility of a correction of blood deposition by the veno-constructor reflex [3, 9] is lessened. We hope that this question will be discussed in detail in the report of Prof. Gauer. On our part, we should like to concentrate attention upon the significance which the condition of resistive vessels acquires in the area of increased hydrostatic pressure under these conditions.

As we tried to argue with the results of simulated experiments on animals, a long reduction in arterial pressure in resistive vessels leads to an increase in their extensibility, and practically completely eliminates the vasoconstrictive effect of the tonic pulsation of constrictor fibers. If a similar process develops during hypodynamia, even though to a lesser degree, a stronger activation of the discharges of sympathetic constrictors is required to support the hydraulic resistance of the vessels of the lower half of the body, and thereby, of the arterial pressure as well.

It should be obviously recognized that the source of these reflexes is the weakening of the summary flow of impulses from the mechanoreceptors of the heart, the aortic arch, and the carotid sinuses [7]. A generalized influence upon the sympathetic system is characteristic of these areas. As soon as more powerful stimulation is required for the counteraction of the growing expandibility of the resistive vessels, then the counteraction is also reflected in the frequency of the heart beat.

In our view, the augmentation after a hypokinetic experiment of responsive reactions to the orthostatic action or to the creation of negative pressure
around the lower half of the body, which is especially clearly seen in a further /9
acceleration of the heart beat, confirms the stated position. More frequent contraction of the heart increases the mean arterial pressure. It is evident

that its magnitude is a fine index of the tonic condition of resistive vessels. If, for instance, the mean pressure does not increase with accelerated heart contractions, one can think of an insufficiency of the compensatory reactions of the resistive vessels to expansion.

Dynamic measurements make it possible to detect the start of decomposition whose end is an orthostatic collapse. It can be discovered that the drop in arterial pressure is preceded by an elevation of the minute volume and an increase in pulse frequency (Figure 5). Evidently, this is a reflection of the incipient lowering of the tonus of resistive vessels at a still maintained relatively high arterial pressure.

During orthostatic tests, we were always especially attentive to an elevation in the minute volume; for, at a subsequent stage, a progressive lowering of the tonus of resistive vessels leads to a drop in arterial pressure of a magnitude that is clearly insufficient for the support of systemic blood flow, with all the consequences resulting from it.

We also desired to investigate some materials obtained by the tragically lost crew of the Salyut Soviet space station by spacecraft commander Lt. Col. G. T. Dobrovol'skiy, flight engineer V. N. Volkov, and research engineer V. I. Patsayev.

The same indices were recorded aboard the Salyut space station as were measured during the simulation of weightlessness.

The investigations were carried out at rest and during functional tests with /10
the production of negative pressure around the lower half of the body, or with a measured physical load. Periodic observations with recording of the mentioned indices were begun on the fourth day of flight, and were repeated every three or four days up to the 22d day (Figure 6).

By analyzing the hemodynamic changes in flight, we first turn our attention to the magnitude of the minute volume of blood circulation. This was approximately 30% higher than during measurements in the horizontal position before the flight for two members of the staff, spacecraft commander of the ship and the research engineer. The minute volume did not change substantially in the flight [illegible] during two measurements, but during two other measurements, it was increased. If, however, these values are compared with the results of measurements in the standing position, then the relative increment in G. T. Dobrovol'skiy and V. I. Patsayev reaches an order of 50% to 60% during flight.

Thus, in regard to the vertical position on the ground when the effect of gravitation is realized to its full extent, the heart's service increases in weightlessness.

As flight time increased, the pulse frequency in the commander gradually increased, and on the 22d day, it exceeded the initial value by 15 to 16 beats per minute. The pulse frequency of the research engineer on the 5th day was 20 beats higher than the initial frequency, and it remained the same on the 10th and 14th days of flight. Pulse frequency was lower than the initial value for the flight engineer during the first measurements, but from the 10th day on, a tendency developed toward its slight increase.

Arterial pressure in the commander and in the research engineer remained /11 close to the initial magnitudes, although an increase in it was noticed on one of the days. This episode was more marked in the commander: the pressure increase reached 20 to 25 mm Hg. In both cases the pulse pressure did not change. The increase in the diastolic pressure was the most distinct for the flight engineer on individual days.

On different days, the velocity of pulse wave in the flight engineer and research engineer varied by a maximum of 25% to 30%. It increased by 60% in the ship commander on the 4th and 13th days, but on the 16th day, it became somewhat lower than the initial value.

A shortening of the phase of the isovolumetric systole of the heart developed in two members of the crew during the flight.

In this phenomenon, as in the increase of the minute volume of blood circulation, a very obvious difference can be noticed in the hemodynamic condition during flight, if it is compared with the conditions of clinostatic hypodynamia (Figure 2).

The elevation of the minute volume of blood circulation in weightlessness of course requires explanation. The simplest explanation is to suppose that a long maintained situation of an increased diastolic filling of the heart develops. But, it is hardly possible to doubt that the process of diminution of the total volume of blood through the excretion of water will reach saturation at some moment. It seems to us interesting to pose for discussion the question of whether the activity of the Henry-Gauer reflex is limited by the dehydration phenomenon [7]. /12

The most essential question, of course, concerns the reactions of the cardiovascular system at the moment when the demands for its activity are increased.

On the 13th day of flight, the research engineer responded to the production of the same magnitude of negative pressure around the lower half of the body as on the ground with the same increase in pulse frequency (Figures 7, 8). However, the initial pulse is more frequent. The mean arterial pressure increases, and it is especially marked toward the end of the action. The velocity of pulse-wave spread increases, and the change in the relative length of the phase of cardiac cycle is emphasized.

The dynamics of minute volume maintain the same individual trend as on the ground, but the absolute values of deviations are larger.

An increase in frequency developed in the pulse by 20 beats per minute in the ship commander during flight, in contrast to the ground data, although the initial value was also higher by 14 to 15 beats. On the ground, the arterial pressure and the pulse-wave velocity are practically unchanged. In flight, however, pressure gradually dropped during the test on the blood. The pulse wave velocity increased. The drop in the mean pressure, which from the second half of the test occurred on the background of a relative increase in the minute volume does not look entirely favorable. This forces us to think of a possible subcompensation which is connected, it seems to us, with the increasing pliability of the resistive vessels to forces that weaken their circular dilatation.

In conclusion, we note that a small physical load, especially in V. N. /13
Volkov, was often accompanied by acceleration of the pulse and increase in arterial pressure. In response to measured physical load for one minute, which in force did not exceed an average of 1100 kg, a larger increase arose in the minute volume of blood circulation than was expected. It was associated with an increase in pulse pressure. However, a marked drop in the diastolic pressure was noticed immediately after work.

Episodically intermittent amplitudinal oscillations were noted in the pulse during the flight. Waves of the second order were more marked, especially at functional loadings.

Thus, the flight of the crew of the Salyut space station which was made in a large ship, and with the performance of special trainings, corroborated the presence of changes in blood circulation. Finally, the elucidation of the mechanism of their development needs further investigations.

Undoubtedly, the mysteries which the problem of blood circulation in weightlessness presented to us would be smaller if we could deeper understand the mechanisms of orthostatic stability on the ground. But as soon as we start to study human blood circulation in weightlessness, it can be hoped that this "ground" problem will be solved in such a complex manner. Nevertheless, as we tried to indicate, attention must already be turned also to an area which is, at first glance, more suited to the gravitation factor, to resistive vessels. In the final analysis, however, "blood circulation in weightlessness and in the period of readaptation" is a very profound and complicated problem of the mechanisms of long-range adaptation of organs of the regulatory systems to loads.

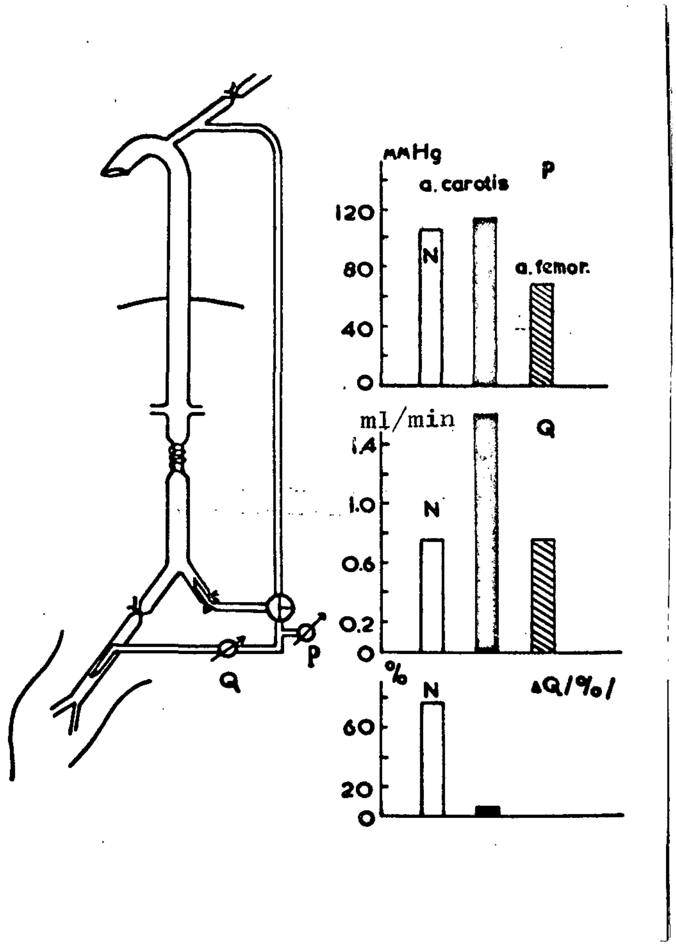

Figure 1. Outline and results of the experiments for producing a chronic lowering of the arterial pressure by contricting the aertic lumen of rats above its bifurcation. 14

On the graphs, from top to bottom:
mean arterial pressure (mm Hg);
blood circulation through a rear leg (in ml/min.)
effect of sectioning the sciatic and femoral nerves (in % of blood circulation before sectioning).

Average data of the control experiments
(14 animals -- white columns;
average date of experiments on 5 animals with constriction of the aortic lumen:
black columns -- blood supply to the leg from the carotid artery;
hatched columns -- blood supply to the leg from the femoral artery).

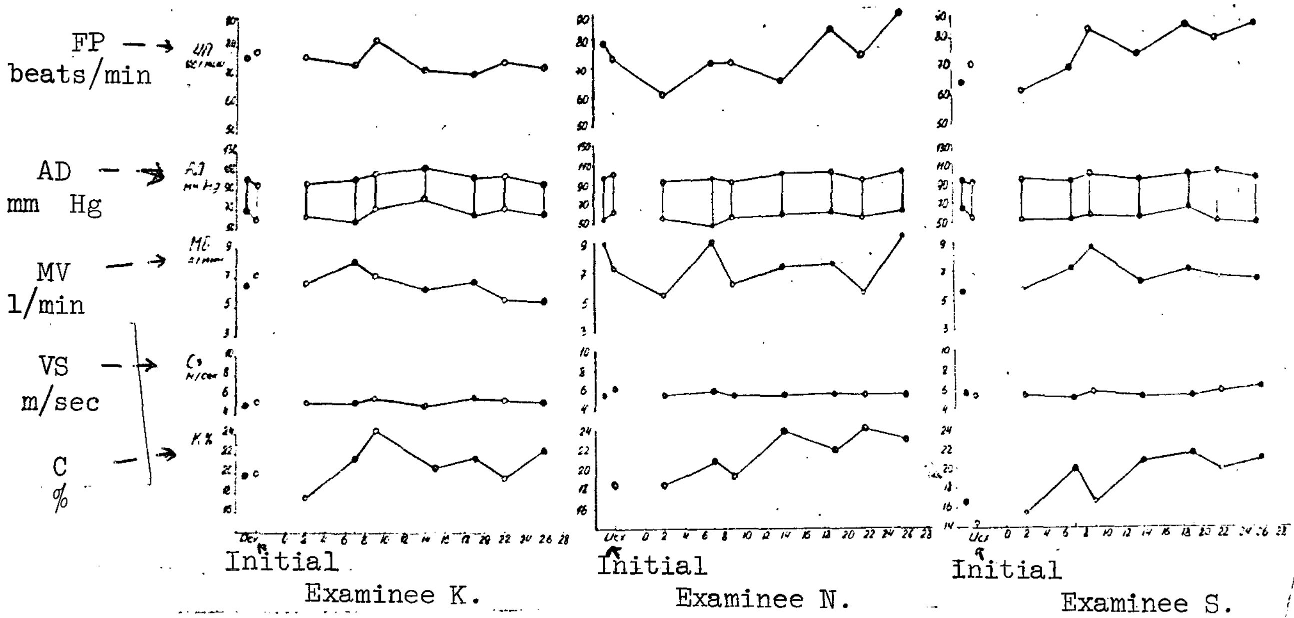

Figure 2. Indices of the condition of the cardiovascular system at rest in three examinees during a 30-day experiment with clinostatic hypodynamia.

FP- frequency of pulse; AD - marginal systolic and diastolic pressure; MV- minute volume of the blood; VS- velocity of pulse-wave spread over the sector "heart- brachial artery"; C %- ratio of the length of isovolumetric systole of the left ventricle to the length of the period of blood expulsion.

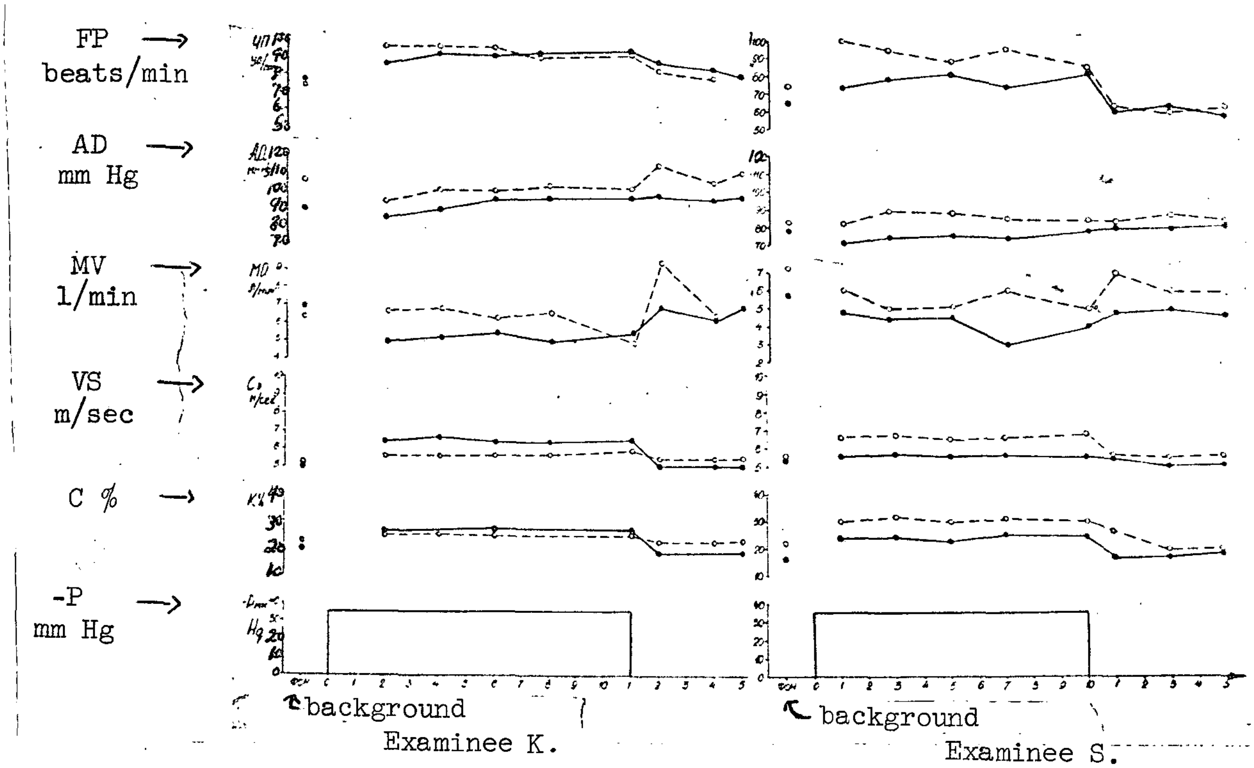

Figure 3. Changes in hemodynamic indices in two examinees during the production of a negative pressure around the lower half of the body (____ in the original condition; ----- in the second week of clinostatic hypodynamia).

Key, the same as on Figure 2.

AD- average arterial pressure; VS- velocity of the spreading of the pulse wave over the sector "heart-femoral artery"; P- value of negative pressure. /15

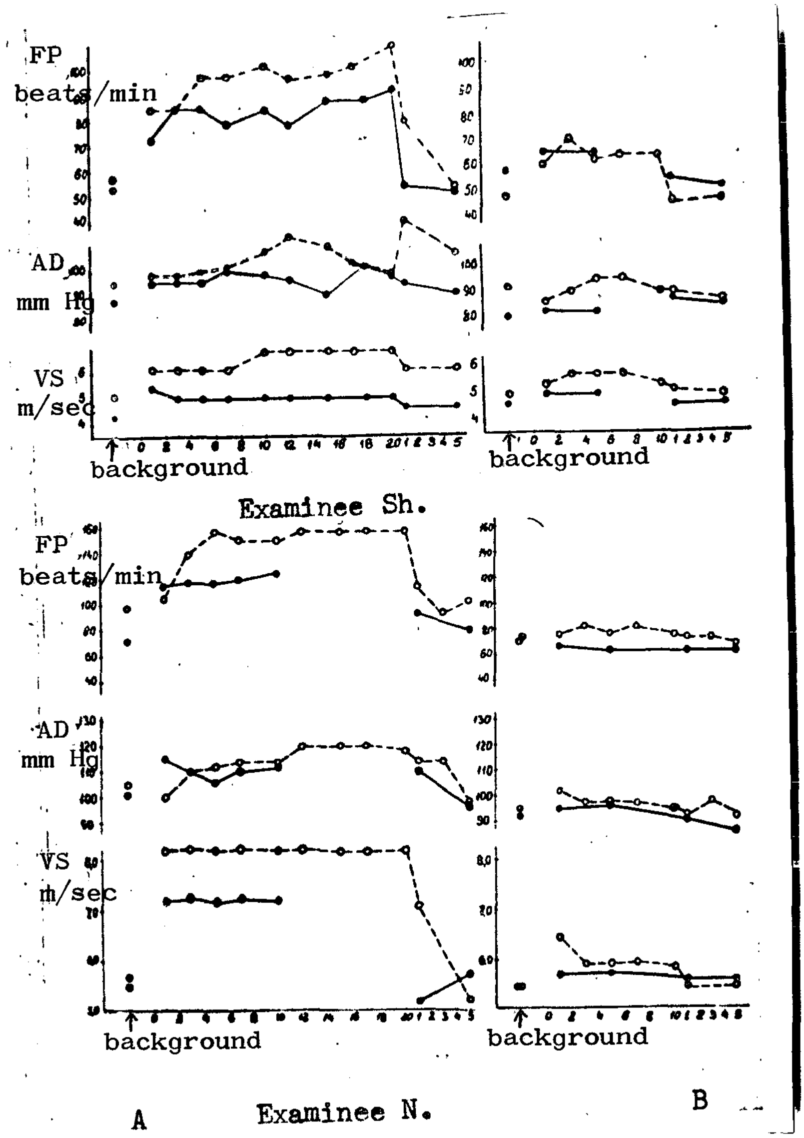

Figure 4. Comparison of the changes of indices of hemodynamics in two examinees during a passive orthostatic test (A), and during a test with the production of a negative pressure (B) around the lower half of the body (___ in the initial state and --- after a 30-day clinostatic hypodynamia).

Key, the same as on Figure 3.

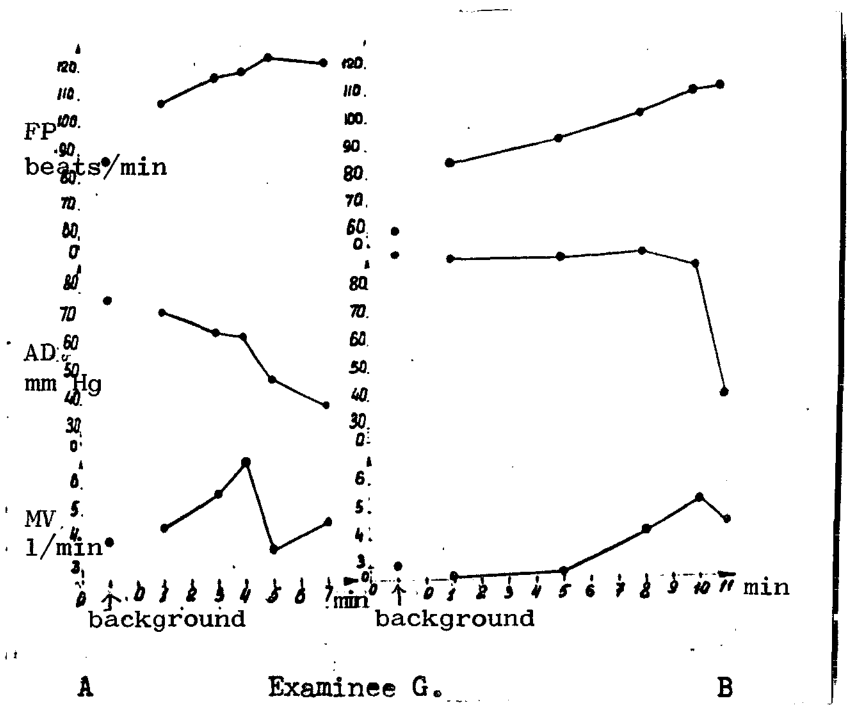

Figure 5. Changes in hemodynamic indices in examinee G with poor tolerance of the passive orthostatic test (A) and during test with production of a negative pressure (-60 mm Hg) around the lower half of the body (B).

Key, the same as on Figure 3.

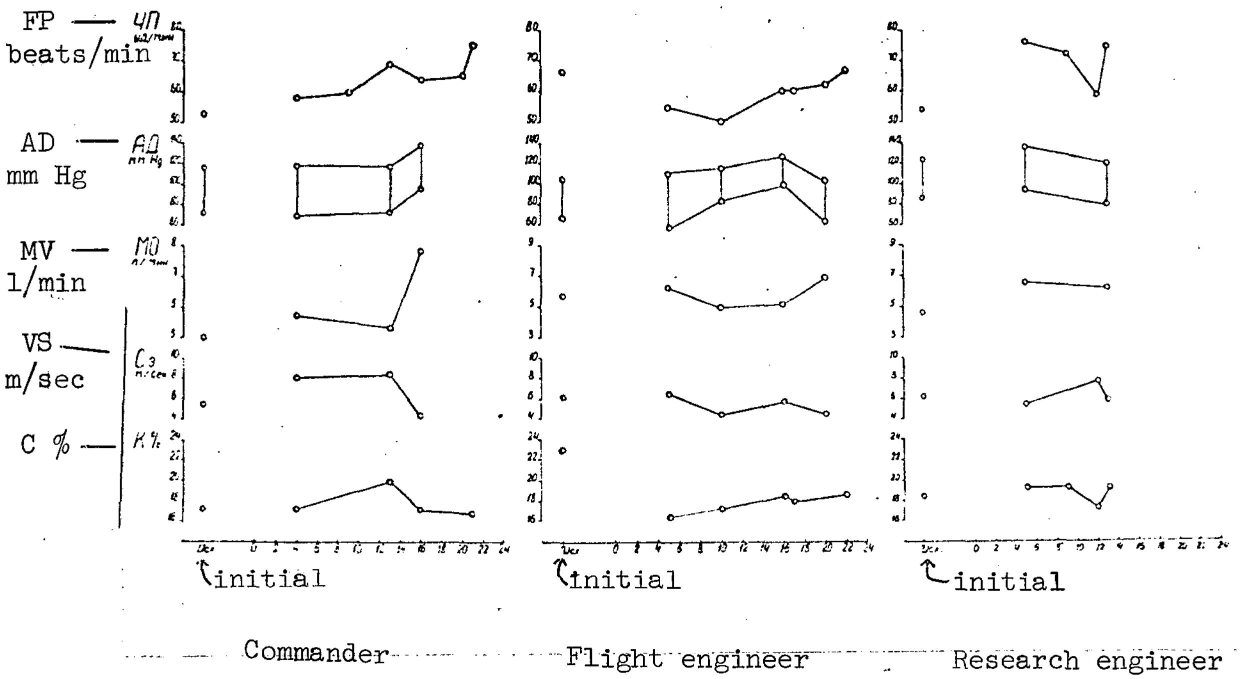

Figure 6. Indices of the condition of the cardiovascular system in crew members of the Salyut Soviet space station, recorded at rest on various days of flight.

Key, the same as on Figure 2.

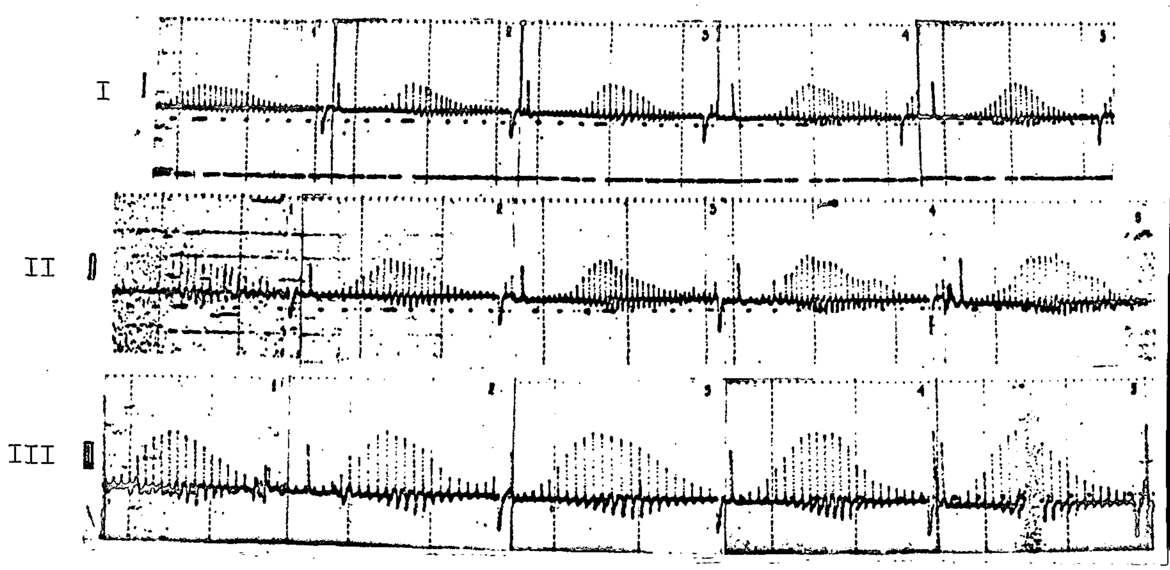

Figure 7. Tacho-oscillogram of the humeral artery of V. I. Patsayev (I) and G. T. Dobrovol'skiy (II), recorded before a functional test with production of a negative pressure around the lower part of the body (1), at 30 secs (2), 2 mins (3), 4 mins (4), and 5 mins (5) of test, and of G. T. Dobrovol'skiy (III) recorded in the recovery period: at 30 secs (1), at 2 mins (2), at 3 mins (3), at 4 mins (4), and at 5 mins (5).

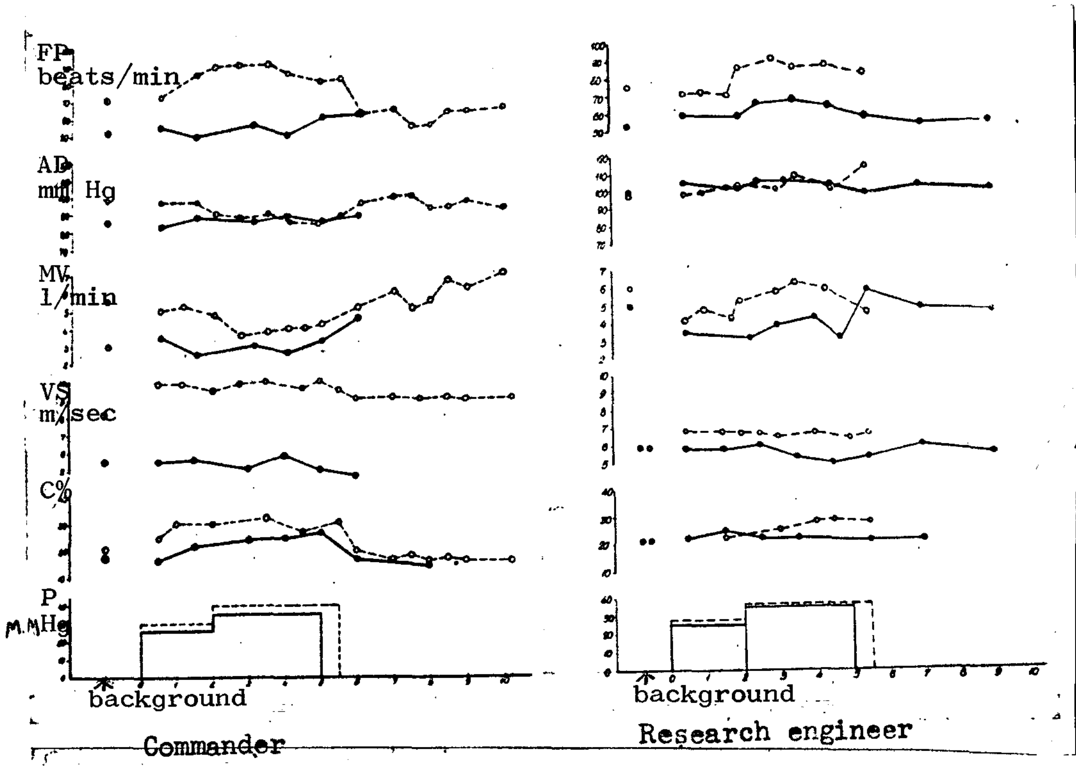

Figure 8. Changes in hemodynamic indices in the commander of the Salynt space station and in the research engineer in response to a test with production of negative pressure around the lower half of the body before flight and on the 13th day of flight.

Key, the same as on Figure 3.